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14. ABSTRACT
The objectives of the proposed research are (1) to develop a focused schlieren optical system for laboratory-scale demonstration for spray and combustion studies, (2) to develop new data processing techniques for obtaining velocity field, and (3) evaluate field-of-view, depth-of-focus, and image resolution issues. Experiments were performed to visualize and measure velocities in a gas flow with liquid droplets. The experiments used a focusing schlieren optical system to visualize the refractive disturbances of the gas flow in a narrow depth of field. The

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Report Title

ABSTRACT

The objectives of the proposed research are (1) to develop a focused schlieren optical system for laboratory-scale demonstration for spray and combustion studies, (2) to develop new data processing techniques for obtaining velocity field, and (3) evaluate field-of-view, depth-of-focus, and image resolution issues. Experiments were performed to visualize and measure velocities in a gas flow with liquid droplets. The experiments used a focusing schlieren optical system to visualize the refractive disturbances of the gas flow in a narrow depth of field. The images were recorded with a high-speed digital video camera for allowing PIV processing to identify velocities in the field of view. The high-speed images were processed to identify motion between frames to obtain velocity vectors. The processing currently picks up both the turbulent structure motions along with the water droplet motion. Future work involves developing methods to separately measure the particle and gas stream motions.

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Scientific Progress

Technology Transfer

FOCUSED-SCHLIEREN-BASED SEEDLESS VELOCIMETRY FOR SPRAY AND COMBUSTION STUDIES

(Contract # W911NF-13-1-0308)

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1. Objectives

The objectives of the proposed research are (1) *to develop a focused schlieren optical system for laboratory-scale demonstration for spray and combustion studies*, (2) *to develop new data processing techniques for obtaining velocity field*, and (3) *evaluate field-of-view, depth-of-focus, and image resolution issues*. The focused schlieren approach overcomes the limitations of standard line-of-sight schlieren by emphasizing a focused planar region of the flow, thereby reducing interferences from environmental thermal gradients and allowing seedless velocimetry within the flow.

Spectral Energies, LLC in collaboration with Pennsylvania State University, developed a focused schlieren system for wind tunnel applications where the seeding was prohibitive. This system was demonstrated in the Air Force Research Laboratory (AFRL)'s trisonic wind tunnel facility at Mach 3 flow conditions. We propose to extend this approach to vortex dominated flows and transition studies. This technique can prove extremely valuable for several reasons: (a) focused schlieren extracts data in a plane rather than in a path-averaged manner, minimizing interferences from external density gradients that often hamper the use of standard schlieren, (b) planar schlieren enables velocity to be extracted from unambiguous regions, (c) it is often difficult to seed regions undergoing significant expansion, and (d) eliminating particle seeding can significantly improve productivity by eliminating window cleaning requirements in laboratory facilities.

2. Background

Traditional schlieren optics visualize refractive disturbances throughout the length of the optical path, thus providing an integrated image of a refractive disturbance field. Although schlieren optics are useful for investigating overall refractive fields, they do not provide any information on the spatial distribution of refractive disturbances along the optical path. Focusing-schlieren optics, however, can be used to visualize only the refractive disturbances in a limited volume along the optical path. Focusing schlieren optics can thus, in principle, be used to explore a three-dimensional refractive field by incrementally visualizing individual "planes" along the optical path but perpendicular to it.

Focusing schlieren, as we apply it, is a lens-and-grid type schlieren technique. The basic optical setup is diagrammed in Figure 1. The non-parallel light through the system causes only one "plane" (or near-planar volume) in the "test region" to be in focus at a time, determined by the simple-lens placement and camera focal setting. With a given camera setting, the camera images only refractive disturbances in this "region-of-focus", which can then be translated along the optical axis throughout the test region by changing the simple-lens placement and camera focus setting.

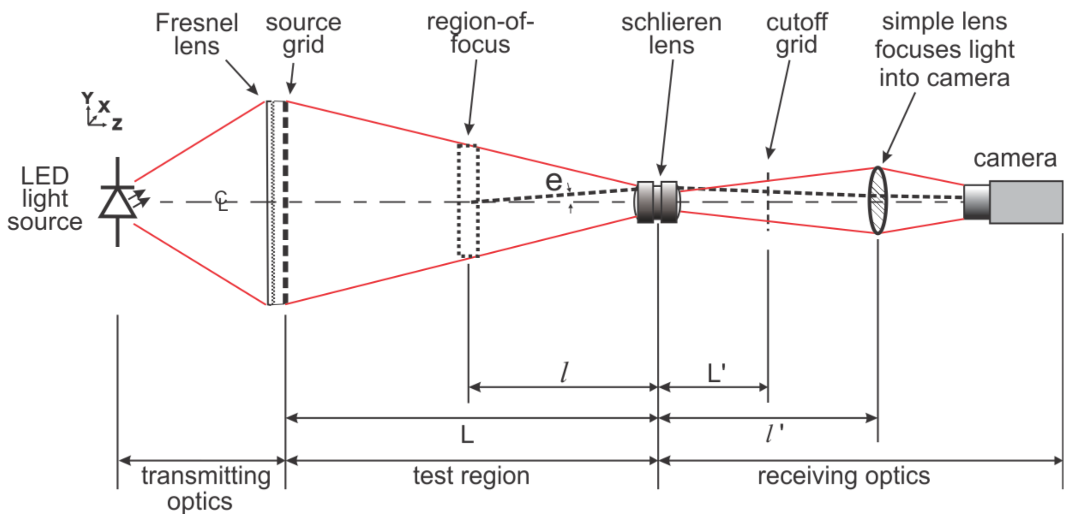

Figure 1: Schematic of a focusing schlieren optical system (Settles, et al.).

Refractive disturbances that are outside of the region of focus are defocused and blurred so that they are essentially not resolved in the final image recorded by the camera. The further a disturbance is located from the region of focus, the more significantly it is defocused in the image. For the schlieren image velocimetry (SIV) purposes, the focusing schlieren optics allow sharp focus and resolution of turbulent structures within the region of focus while structures outside this region are not resolved well enough to affect the measurement. During the SIV processing only the sharply-resolved structures are used in the correlation procedure, and thus a near-planar velocimetry measurement is obtained for structures only in the region of focus.

The focusing effect is shown in Figure 2 for a simple helium jet issuing into the air. When the jet is located at the center of the region of focus (left-most image) the refractive turbulent mixing structures within the jet are clearly resolved, as are the threads on the outside of the nozzle itself. As the jet is moved closer to the schlieren lens and away from the region of sharp focus (images progressing to the right), the turbulent structures within the jet are resolved less, until they are ultimately not resolved at all (right-most image). Some residual "blur" from the jet is still present, but it is insignificant and does not affect the visualization of other structures in that plane or any SIV correlations.

The depth of focus of the optical system can be determined as the distance over which refractive turbulent structures are clearly resolved. For the particular system used to record the images in Figure 2, the depth of focus is approximately +/- 1 inch or +/-25 mm, centered at the plane shown in the left-most image. Outside this region-of-focus, velocimetry of turbulent structures no longer occurs due to image blurring. This depth of focus can be improved with the design of appropriate optics.

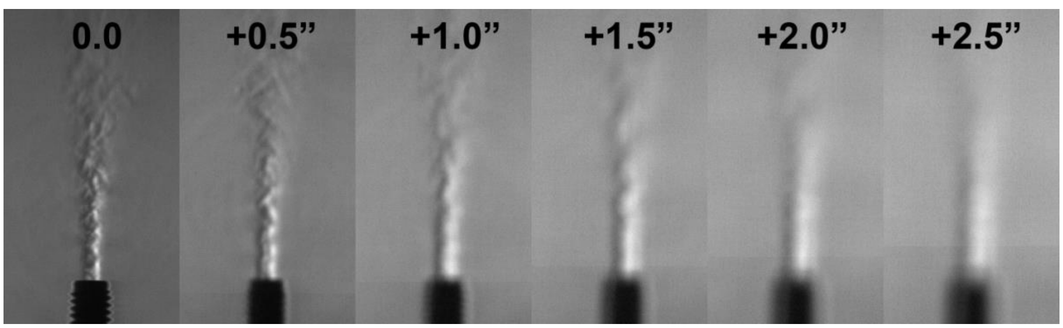

Figure 2: An image series showing the focusing effect of a focusing schlieren system.

With this visualization the air jet was translated along the optical axis to define the region of focus. The region of focus can also be translated around a fixed jet location by adjusting the simple lens, camera position and focus.

The field-of-view of a focusing schlieren system is defined by the geometry of the system and the optical components. In general, the system can be designed to obtain any field-of-view of interest. The field-of-view must be balanced with the desired depth-of-focus and the camera resolution in order to properly image the desired refractive field with sufficient spatial resolution for velocimetry measurement.

3. Progress

Experiments were performed to visualize and measure velocities in a gas flow with liquid droplets. The experiments used a focusing schlieren optical system to visualize the refractive disturbances of the gas flow in a narrow depth of field. The images were recorded with a high-speed digital video camera to allowing PIV processing to identify velocities in the field of view.

3.1 Experimental Setup

The experimental setup and photograph of the focusing schlieren system is shown in Figure 3. The camera is not shown on the system in the image, but a Photron SA-X2 high-speed digital video camera was used to record the images. The images were recorded at 12,500 frames per second with an exposure time of 10 microseconds. A 2-LED array was used as the light source.

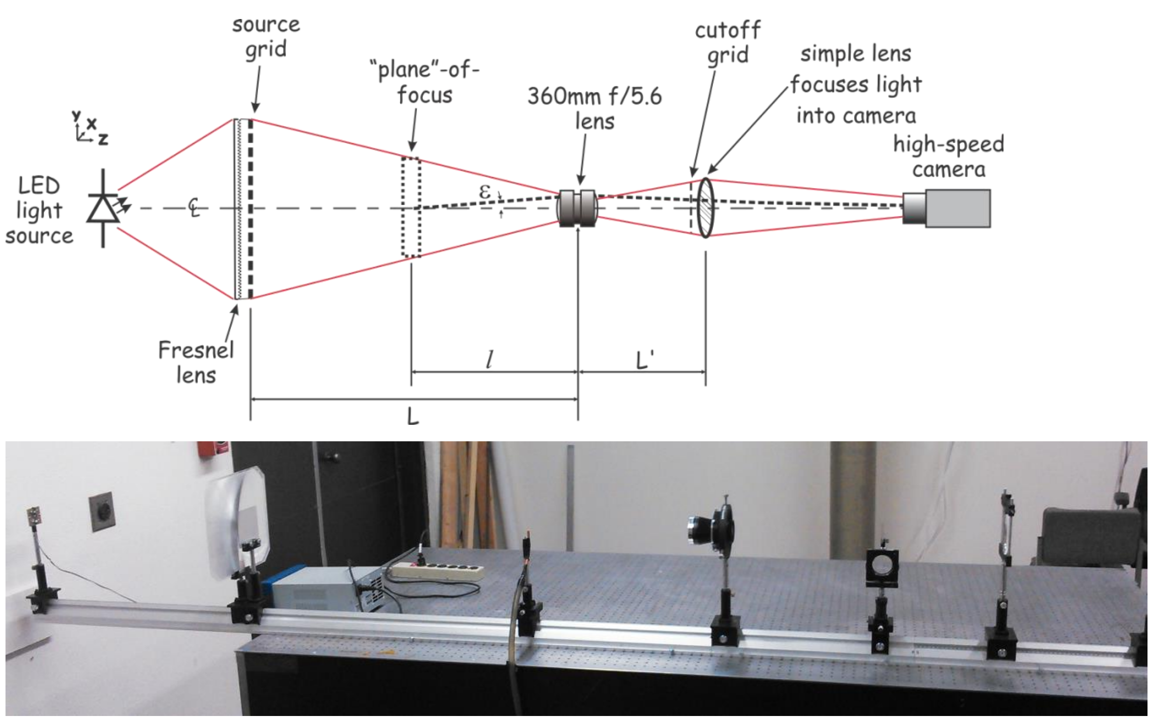

Figure 3: Schematic of the focusing schlieren system (top) and photograph of the system (bottom).

To create the liquid jet in a gas stream, helium was used as the carrier gas and water was used as the liquid. The water was injected into the gas line upstream of the exit tube. The exit of the gas was a straight-walled pipe with a diameter of approximately 5mm. The water droplets formed in an unsteady process and were not necessarily evenly-distributed throughout the gas stream.

3.2 Experimental Results

The focusing schlieren optical system was tested to identify the depth of focus for visualizing refractive disturbances. The straight-walled pipe with helium flowing through it was used to evaluate the depth of field. Experiments were performed where the helium jet was transitioned along the optical axis from the plane of focus in both directions. Individual still images of the jet at different locations are shown in Figures 4 and 5.

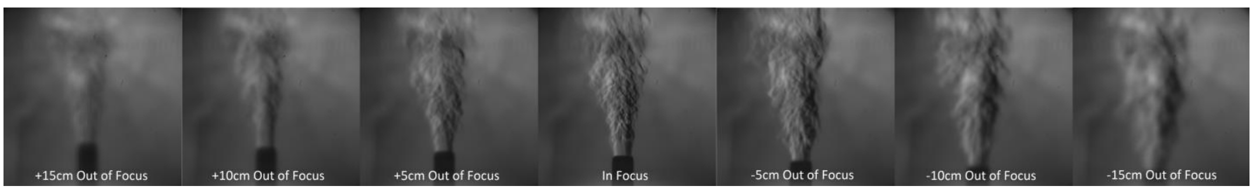

Figure 4: Focusing schlieren images demonstrating the focusing effect as the helium jet is transitioned along the optical axis. The position of best focus is in the middle of the compilation.

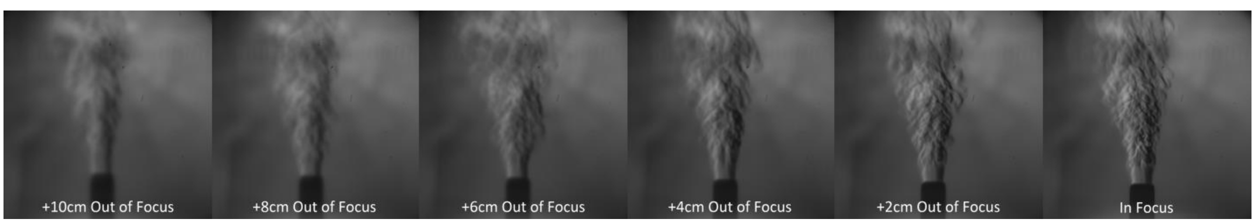

Figure 5: Detailed images of the focusing schlieren effect on the helium jet.

The depth of focus of the system was evaluated by examining the images in Figures 4 and 5 to identify at what location individual turbulent structures in the jet become non-distinct. From the images in Figure 5 the depth of focus was found to be about +/- 6cm for the system in this arrangement.

This depth of focus is dependent on the use of the "simple lens" shown in Figure 3. This lens increases the depth of focus, but improves the light capture for the setup. The experiments here using the current LED array and high-speed camera required the use of this lens. Future experiments could use a larger LED array and then will not need the lens and will allow a reduced depth of focus.

High-speed images were recorded of the jet with water injection. Video files of the process show that the water injection is highly non-uniform and unsteady. The video also shows that as the water is ejected the jet flow is distorted. The interactions between the jet and the liquid droplets is clearly observed in the videos. The breakup of the liquid can also be observed as it interacts with the turbulent structures in the jet. Example images from the video file are shown in Figure 6.

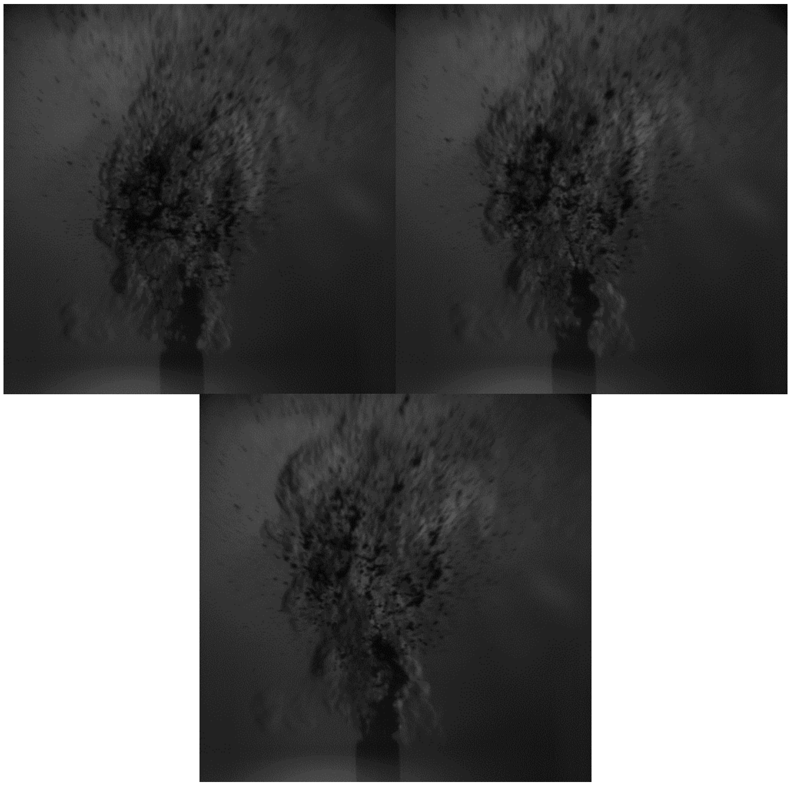

Figure 6: High-speed images of the helium jet with water droplets, recorded 0.0004 seconds apart. The images show the breakup and dispersion of the water jet and the interactions with the turbulent structure of the jet.

The high-speed images were processed to identify motion between frames to obtain velocity vectors. The processing currently picks up both the turbulent structure motions along with the water droplet motion. Future work could develop methods to separately measure the particle and gas stream motions. A simple vector plot from the processing of one image pair is shown in Figure 7.

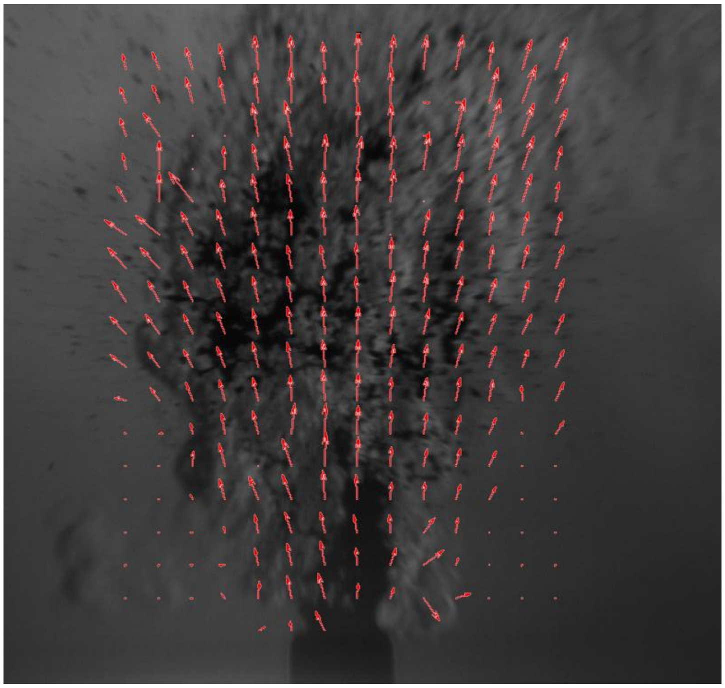

Figure 7: Vector plot for the analysis of a single image pair from the high-speed image sequence. The vector magnitudes have an average of approximately 7 m/s.

4. Future work

Improvements to the system and measurements could be made in future efforts, including:

- Larger LED array to eliminate the need for the “simple lens”, thus reducing the depth of focus
- Smaller depth of focus could be obtained by shortening the overall system if desired. The current system is approximately 3.5m long.
- Addition of laser illumination to illuminate droplets in a single plane. This could be combined with a colored-beam-splitter to allow imaging from two separate cameras, one viewing only the laser illumination wavelength, and the other imaging the schlieren distortions.
- More uniform liquid injection to allow average velocity vectors
- Improved PIV processing
- Droplet sizing and distribution statistics.

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